Implementing Distributed Control Algorithms within ZELDA

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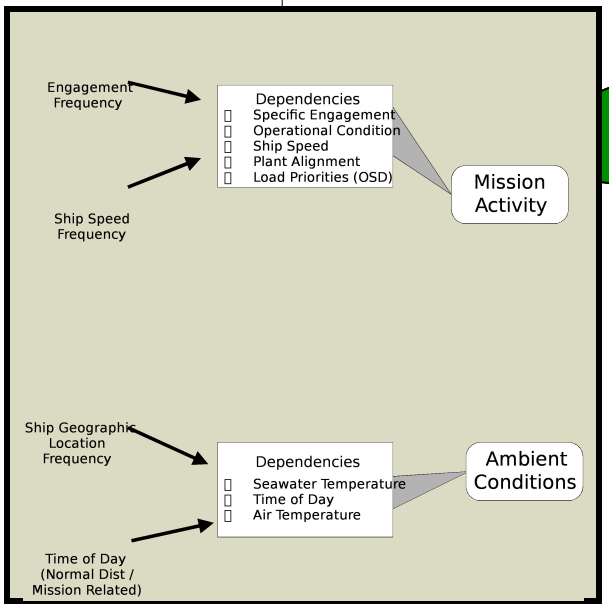
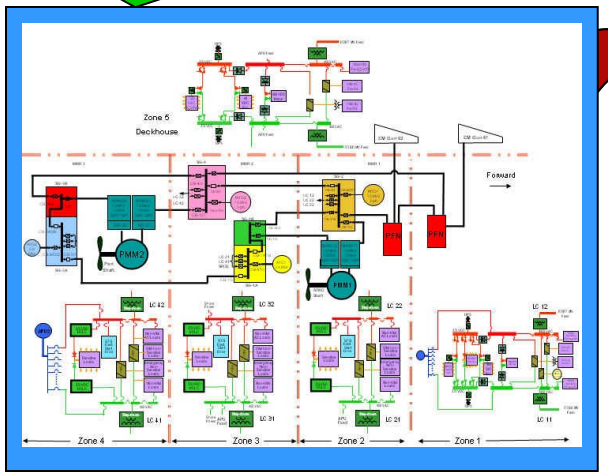
ZELDA (Zonal Electric Design Analysis) is an Event Driven, Bulk Energy Flow Model Developed to Incorporate Mission and Operational Context into the System Engineering Process

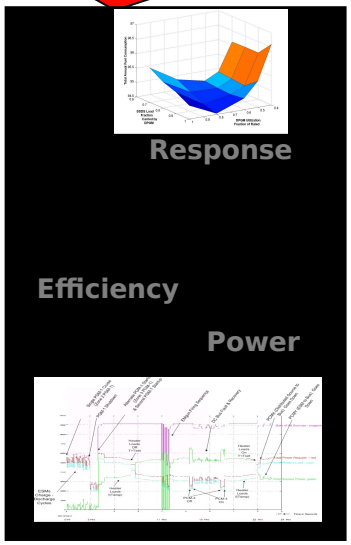
Mission and Operational Impac



Independent & Dependent Input Distributions

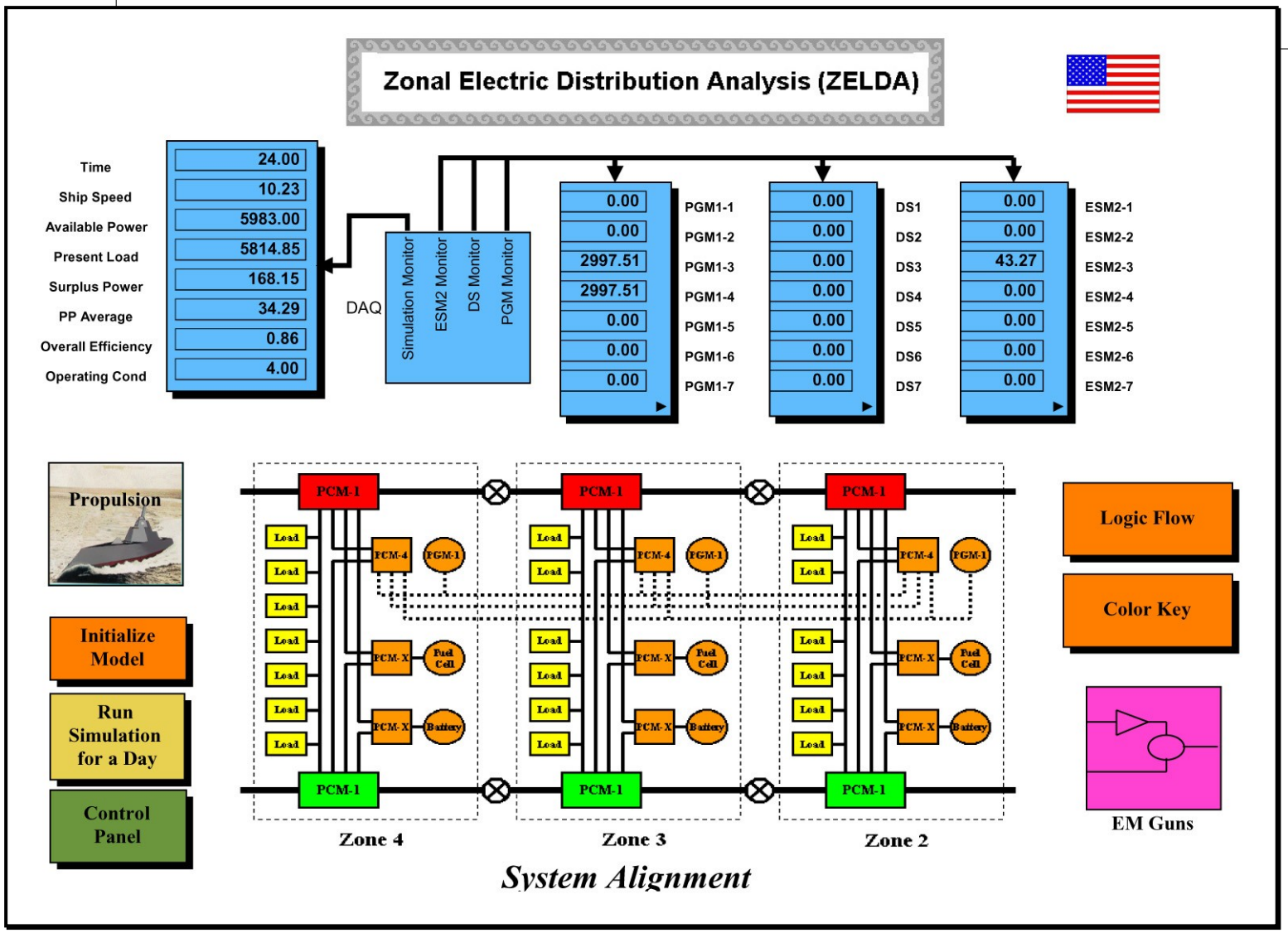


System Model

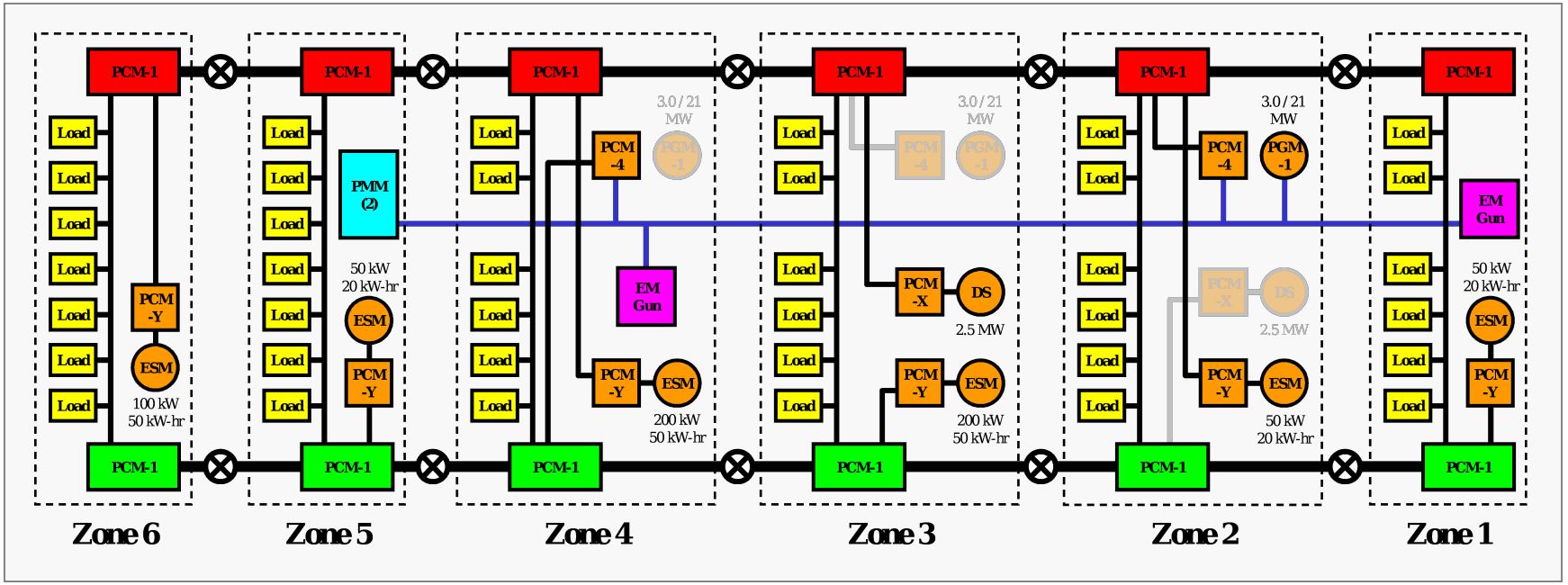


System Response Distributions & Time Histories

Quantify output variability not present in single realizations

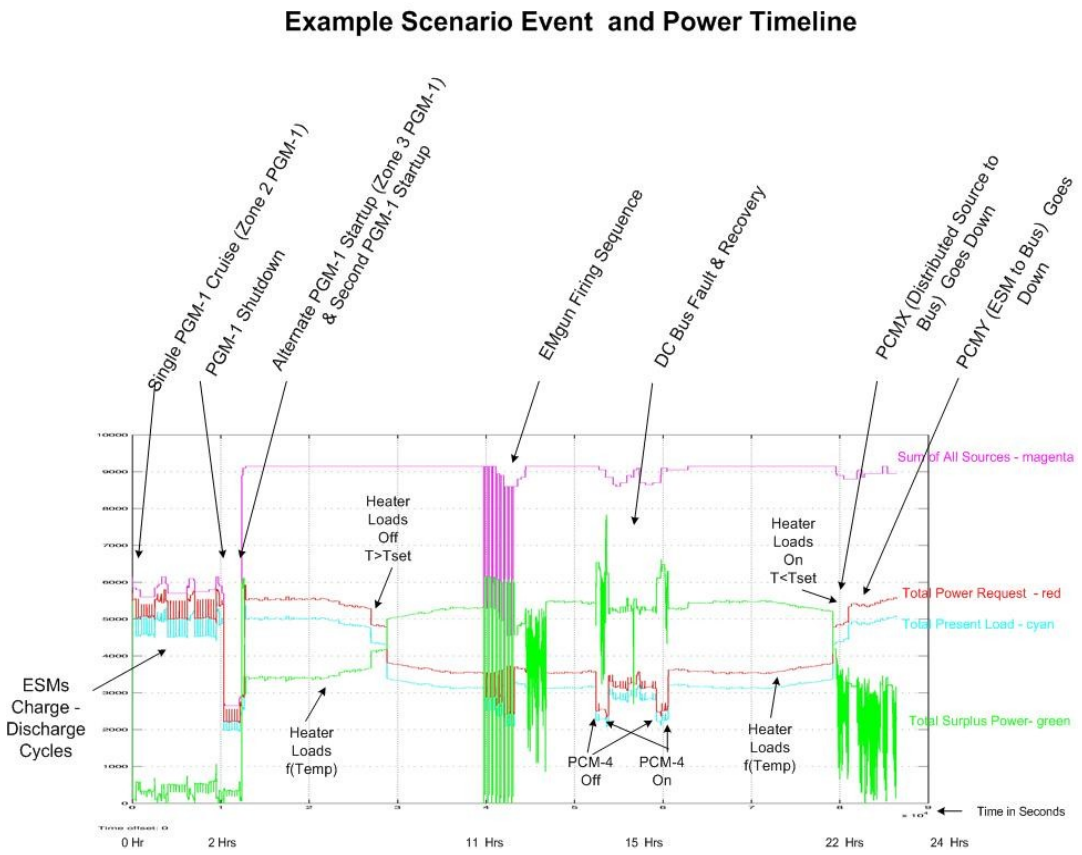

Zonal Electric Distribution Analysis (ZELDA)
Time
Ship Speed
Available Power
Present Load
Surplus Power
PP Average
Overall Efficiency
Operating Cond
24.00
10.23
5983.00
5814.85
168.15
34.29
0.86
4.00
DAQ
Simulation Monitor
ESM2 Monitor
DS Monitor
PGM Monitor
0.00
0.00
2997.51
2997.51
0.00
0.00
0.00
PGM1-1
PGM1-2
PGM1-3
PGM1-4
PGM1-5
PGM1-6
PGM1-7
0.00
0.00
0.00
0.00
0.00
0.00
0.00
DS1
DS2
DS3
DS4
DS5
DS6
DS7
0.00
0.00
43.27
0.00
0.00
0.00
0.00
ESM2-1
ESM2-2
ESM2-3
ESM2-4
ESM2-5
ESM2-6
ESM2-7
Propulsion
Initialize Model
Run Simulation for a Day
Control Panel
PCM-1
Load
PCM-4
PGM-1
PCM-X
Fuel Cell
Battery
Zone 4
Zone 3
Zone 2
Logic Flow
Color Key
EM Guns
System Alignment

System Configuration



Accepts Arbitrary (nearly) Power Architecture and Component Composition

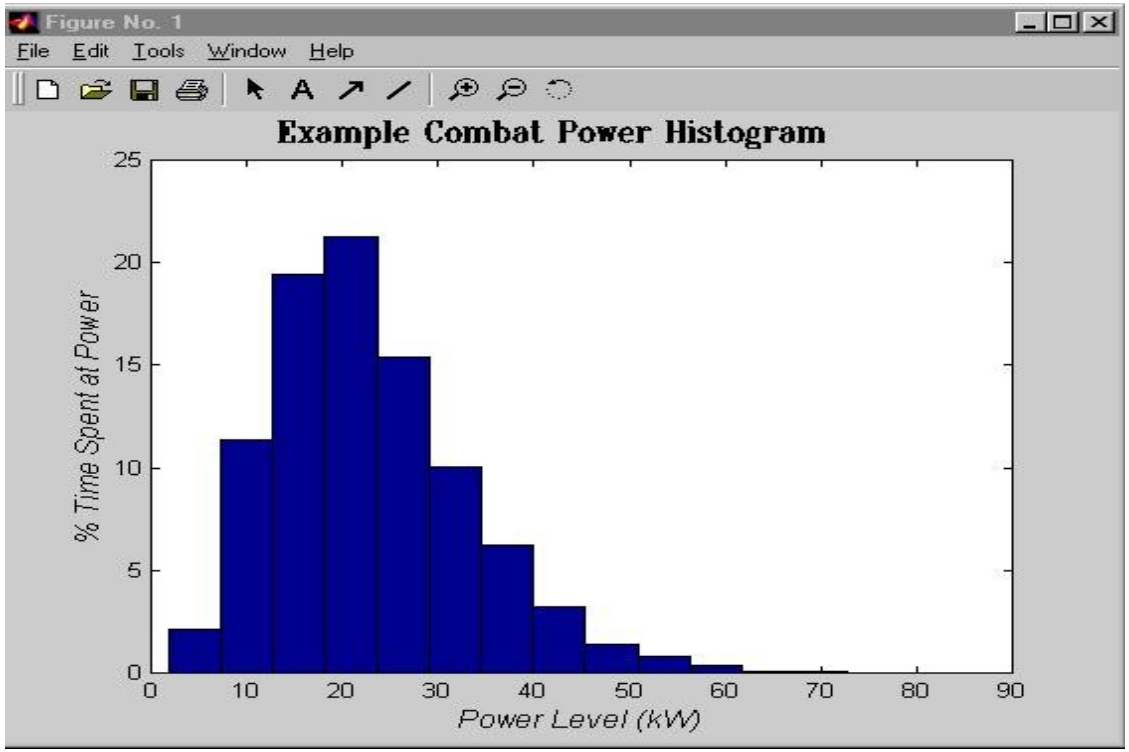
Time Histories


Example Scenario Event and Power Timeline
Single PGM-1 Cruise (Zone 2 PGM-1)
PGM-1 Shutdown
Alternate PGM-1 Startup (Zone 3 PGM-1) & Second PGM-1 Startup
EMgun Firing Sequence
DC Bus Fault & Recovery
PCMX (Distributed Source to Bus) Goes Down
PCMY (ESM to Bus) Goes Down
Sum of All Sources - magenta
Heater Loads Off T>Tset
Heater Loads On T<Tset
Total Power Request - red
Total Present Load - cyan
ESMs Charge - Discharge Cycles
Heater Loads f(Temp)
PCM-4 Off
PCM-4 On
Heater Loads f(Temp)
Total Surplus Power- green
Time in Seconds
0 Hr
2 Hrs
11 Hrs
15 Hrs
22 Hrs
24 Hrs

Reveal Power Management Behavior (Available & Surplus Power)

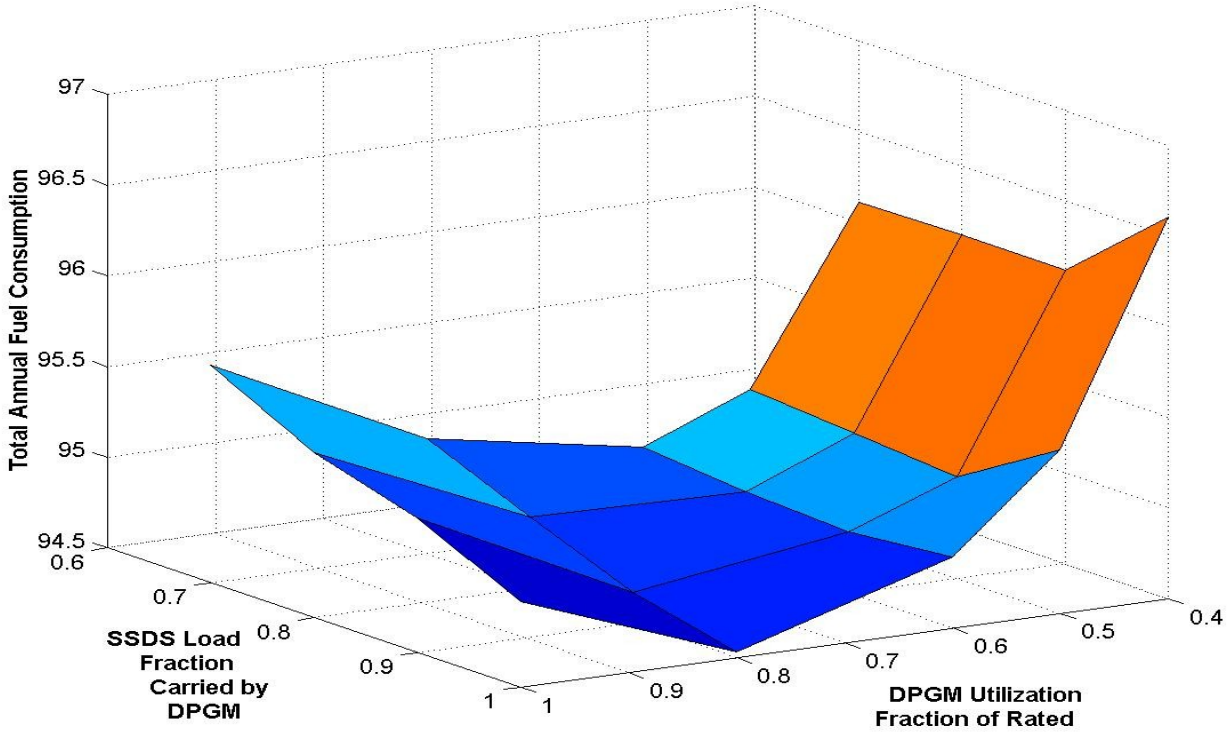
Combat Power Utilization

(Based on Expressed Profile with Variations and Repeated Trials)



Account for Skewed Power Utilization (Probabilistic Design)

Distributed PGM Utilization



Provide Tradeoffs for Component Capacity Allocation

Control System Performance Evaluation

- Model (Zelda) Controls Applicability
  - Large Scale Control Problems
  - Moderate Time Scales
  - Scheduling and Resource Allocation
- Metrics Currently Implemented
  - Available Power
  - Load Outage “Headroom”
  - Source Nearness
  - Post-Hit Available Power
- Metrics / Comparisons Needed
  - Robustness, Tolerance, Complexity, …
- Baseline – IPS (Load Disable Index)
- Agent – NuTech Commodity Market Model

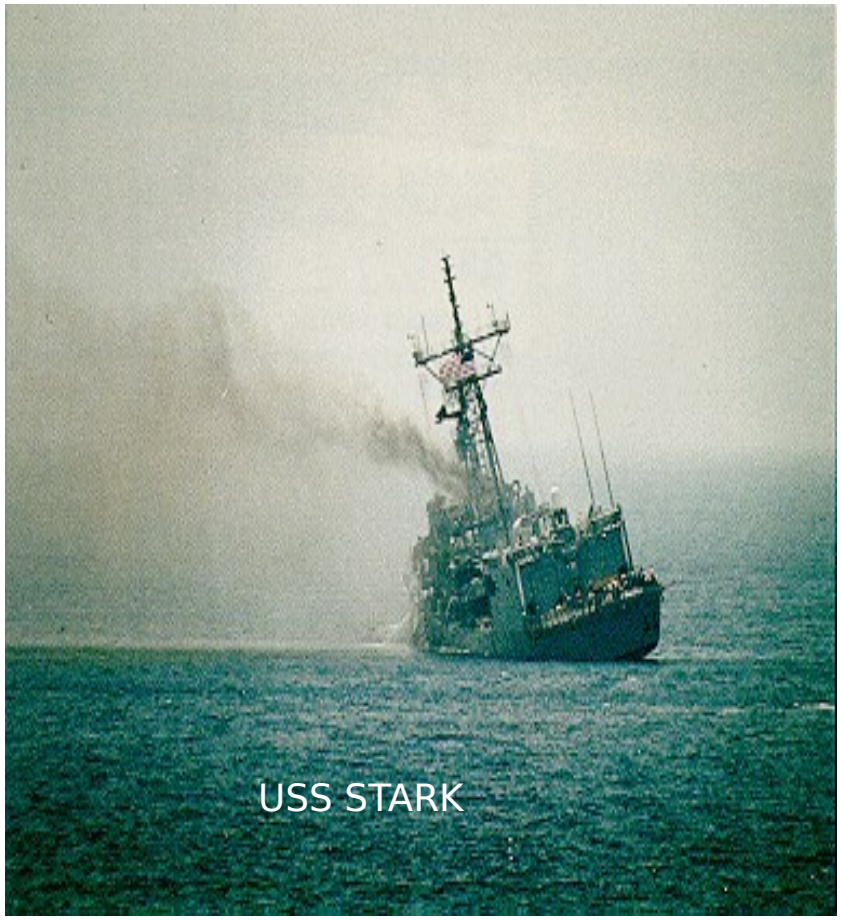
Platform for Resource Management Strategy Evaluations

The Challenge

- NAVY & ONR - Identify and explore technologies and approaches with the potential to dramatically impact the design and operation of control systems
- The NuTech Solutions Team – research a multi-agent approach to address the complex distributed control of a Power Distribution Network
  - What this can mean for future surface combatants:
    1. Reduced Manning
    2. New Operational Capabilities
       - Electric Drive
       - More Electronic Loads
    3. Enhanced Survivability

Why Power Management and Power Distribution Matter

1. USS Stark: struck by 2 air-to-surface missiles. Extensive damage and fire in forward areas of ship and loss of electric power.
2. USS Samuel B. Roberts: struck mine. Flooded engine room and two of three auxiliary machinery rooms and loss of electric power.
3. USS Princeton: struck mine. Considerable damage and loss of electric power



Intelligent Agents Formal definition

- Reactivity
  - Agents react to change in the environment
  - Reactive properties: Agents need to have “sensors” to read the environment and change their status accordingly
    - Fire pumps can read the temperature of the room and the smoke detector. If the temperature is over a threshold and/or there’s more the utility function, or appetite of the fire pump for power grows.
- Pro-activeness
  - Agents have goal-oriented behavior
  - Pro-active properties/ Social Behavior : Agent have to have tailored behavior to attain their goal and coordinate with other agents
    - Some of our loads are willing to compromise their power usage to optimize the overall power usage efficiency
- Social Ability
  - Agents have to interact with other Agents and coordinate with them to achieve a common goal

Market Based Resource Allocation

- Market base resource allocation can be used where there's n > 0 different resource to allocate between *i* agents
- Each agent has a utility function that encodes preferences for each Agent *i,* for each good *g*
- Every agent computes its "consumption bundle"

with $\mathbf{x_i} = [x_{i1}, x_{i2}, x_{i3}, x_{i4}, \ldots, x_{in}]^T \qquad x_{ig} \hat{I} \hat{A}_+$

Producer Agent

- Each Agent receives the price vector $\mathbf{p}$ and
- announce to the “Price Adjustor” its
- production $\mathbf{y}_j$ that maximizes $\mathbf{p} \times \mathbf{y}_j$

Methodology

- Installed the market-based approach into ZELDA.
  - Price is computed based on excess power available to a load
  - We computed the utility parameters for each load to maximize the performance metrics
  - Compared performance of market based approach with optimal utility parameters to the older, priority-based approach

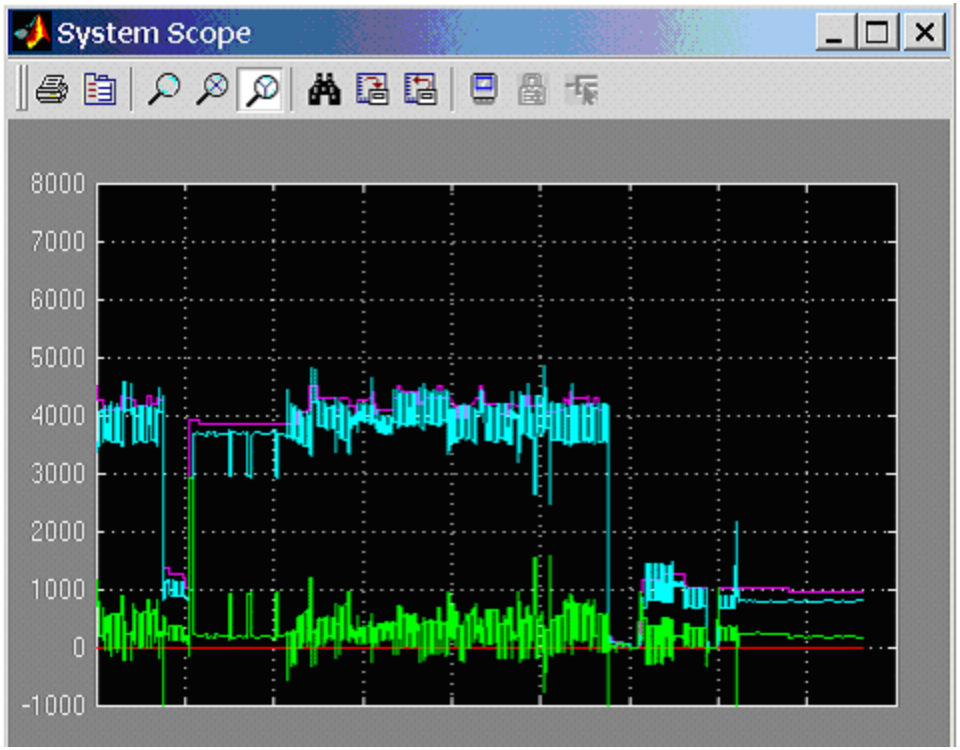
Performance Metrics

- Created three performance metrics for comparing power distribution approaches.
    1) Total Power Supplied / Total Power Requested weighted by load magnitude
    2) Total Power Supplied / Total Power Requested un-weighted
    3) Total Power Supplied / Total Power Requested weighted by load priority

Stability Issues

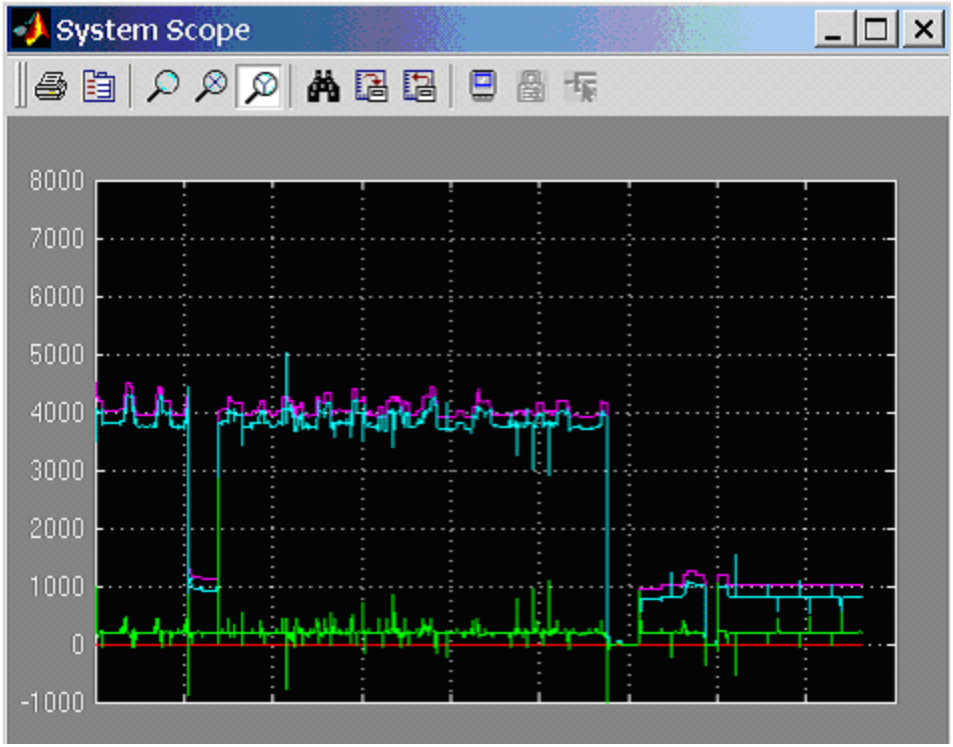
- A problem that frequently arises in power management is that the load configurations chosen by the algorithm are not stable, a problem sometimes referred to as “ringing” or “chatter.”
  - Algorithms compute a load configuration for each time step. An entirely new configuration is computed in the next step. Since the configuration in the previous time step does not play a part in deciding the configuration in the current step, there is nothing to prevent loads from being turned on and off and on and off in rapid succession.
  - While this may satisfy the total power constraints, it is not a good solution for the people manning the ships!

An Example of “Ringing” using LDI Power Allocation



- Cyan = Total Power Supplied
  - Notice the rapid up and down movements. This is “ringing.”

Same Time Period Using Agent-Based Market Mechanism



Power Management Issues in Zelda

- Cyan Trace = Total Power Supplied
- Violet Trace = Total Power available
- Looking again at the previous two figures, we see some brief spikes where the cyan trace exceeds the violet trace.
  - We call these periods “excursions.”
  - Not possible in real life.
  - Possible in ZELDA because mechanism for insuring that power supplied <= power consumed doesn’t respond fast enough to transients.

Power Management Issues in Zelda Continued

- Currently, these excursions last only for a few seconds or milliseconds.
- Earlier in the project, these excursions could continue for hundreds of seconds.
  - This affects our earlier results.
- We have made several improvements to Zelda over the past few months which keep these excursions to a minimum.

Results

Algorithm: Load Disable Index	On	Off
Algorithm: Agent-Based Market	Off	On
LSI #1 TPS/TPR Unweighted	0.58	0.55
LSI #2 TPS/TPR Priority	0.73	0.67
LSI #3 TPS/TPR Magnitude	0.49	0.50
Total PL Excursion Time (Sec)	1216	136
Total PL Excursion Energy (MJ)	440.8	8.1

Results, Continued

- The power distribution method that achieves the highest LSIs is the load disable method.
- Performing slightly less well overall is the agent-based market method.
- The market-based approach exceeds the power available slightly less than the load disable method. The differences in the satisfaction indexes may be partially attributable to the longer time that the load disable index exceeds the available power.

Discussion

- The LDI and the Agent-based Market perform about equally.
- Both are viable approaches to managing and distributing power on a warship.
  - This will help the Navy to meet its goals of reduced manning in the warships of the future.
- Agent-Based Marketing Method has two important benefits:
  - Reduced chatter.
  - It is decentralized.

Discussion, Continued.

- Decentralized approaches offer two potential advantages:
  - Decentralized approaches require less communication, since decisions are made locally, not globally.
  - Decentralized approaches scale nicely as the number of loads increases.

Estimating Load Priorities

- Which loads are most important on the ship?
- How does the importance of the various loads change as the ships situation changes?

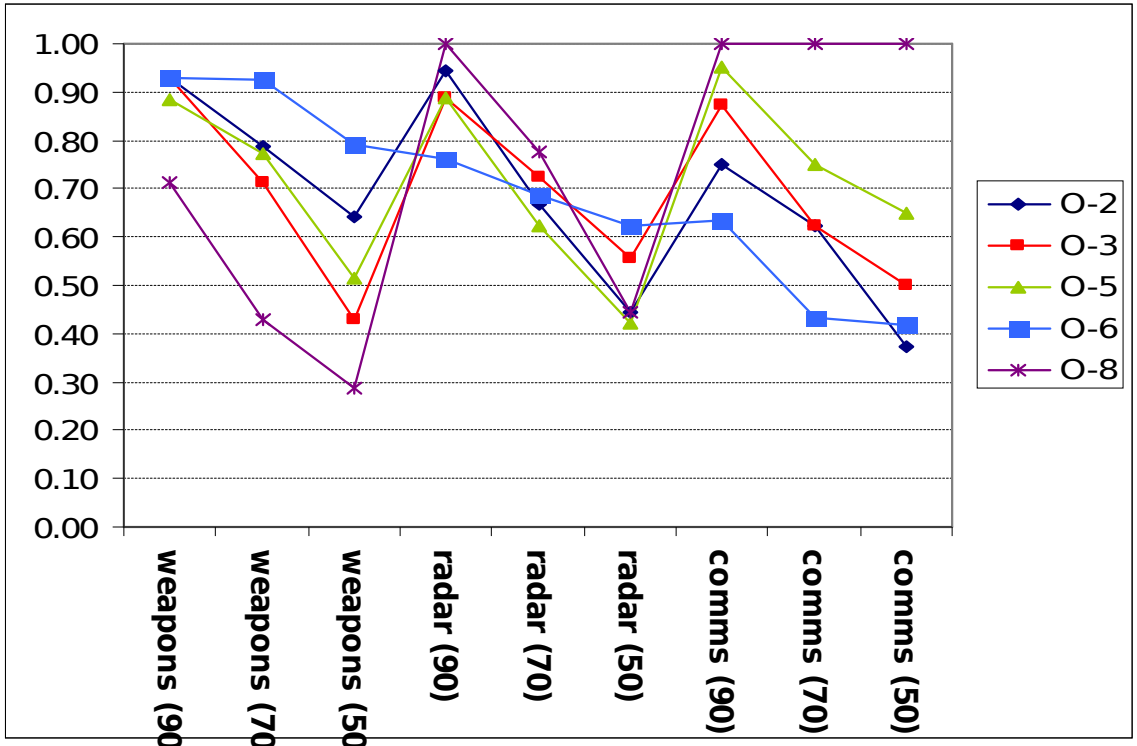
Methodology

- Sent a Survey to 20 Officers at the Naval Postgraduate School.
  - Varied in Rank from O-2 to O-8.
- Asks Naval officers to assign numerical values to the importance of weapons, communications and radar systems under three conditions when a ship is under attack.
  - Adequate – 90% of the ships power is available
  - Partial – 70% of the ships power is available.
  - Minimal – 50% of the ships power is available

Raw Results

	FULL			ADEQUATE			PARTIAL			MINIMAL		
RANK	WPNS	RADAR	COMMS	WPNS	RADAR	COMMS	WPNS	RADAR	COMMS	WPNS	RADAR	COMMS
O-2	35	45	20	30	40	20	25	30	15	20	20	10
O-2	35	45	20	35	45	10	30	30	10	25	20	5
O-3	35	45	20	30	40	20	30	30	10	20	20	10
O-3	35	45	20	35	40	15	20	35	15	10	30	10
O-5	35	45	20	35	35	20	35	15	20	20	10	20
O-5	35	45	20	35	40	15	30	30	10	20	20	10
O-5	35	45	20	30	40	20	25	30	15	20	20	10
O-5	35	45	20	25	45	20	15	40	15	10	25	15
O-5	35	45	20	30	40	20	30	25	15	20	20	10
O-6	35	45	20	30	40	20	20	35	15	15	20	15
O-6	35	45	20	30	45	15	20	35	15	20	20	10
O-6	35	45	20	35	45	10	30	35	5	25	20	5
O-6	35	45	20	30	40	20	25	30	15	18	22	10
O-6	35	45	20	35	35	20	35	15	20	30	10	10
O-6	35	45	20	35	45	10	30	35	5	25	25	0
O-8	35	45	20	25	45	20	15	35	20	10	20	20
Avg	35	45	20	31.6	41.3	17.2	25.9	30.3	13.8	19.3	20.1	10.6

Responses Grouped By Rank and System



Rank	Weapons (90)	Weapons (70)	Weapons (50)	Radar (90)	Radar (70)	Radar (50)	Comms (90)	Comms (70)	Comms (50)
O-2	0.93	0.79	0.64	0.94	0.67	0.44	0.75	0.63	0.38
O-3	0.93	0.71	0.43	0.89	0.72	0.56	0.88	0.63	0.50
O-5	0.89	0.77	0.51	0.89	0.62	0.42	0.95	0.75	0.65
O-6	0.93	0.93	0.79	0.76	0.69	0.63	0.63	0.43	0.42
O-8	0.71	0.43	0.29	1.00	0.78	0.44	1.00	1.00	1.00

Results

- O-8 respondent chooses to operate the comms system at 100% of full power in all three conditions. This causes him to sacrifice power to the weapons system. This strategy differs markedly from the other four ranks who choose to sacrifice power to comms in order to send more power to weapons.
- Looking closely at Table 2, we see a generally upward trend in the value of communication as you move up in rank. A regression through these data yields a slope of +2.6% increase in the value of communications per increase in rank(R^2=0.07). The R^2 is quite low, due in large part to a single O-6 respondent who had a value of zero for communications in the minimal condition. Nevertheless, we conclude that as respondents gain experience and move up in rank, they place a higher value on communications.

Discussion

- Created a new, distributed, power management algorithm and demonstrated its viability.
  - This algorithm had never been applied to warships.
- Collected data on priorities and importances of functional capabilities.
  - We believe this exercise to be the first of its kind.
- We are working to convert both of the above into terms that can be used for more effective naval policy-making.

Summary

- Context Sensitive Design Model for Probabilistic Design View
- Large Scale – Full Power Architecture with Mission, Distributed, and Hotel System Loads
- Flexible “Patch Panel” Architecture and Component Implementation
- Efficient Computation
- Resource Management Strategy Evaluation Platform
  - Baseline Operation with Load Disable Algorithm
  - More Stable Operation with Agent-Based Market Approach
  - Development and Demonstration of Other Concepts
- Open Issues
  - Methodology for Assignment of Load Priorities
  - Development of Mission Capability Metrics